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Window retrofit strategy for energy saving in existing residences with different thermal characteristics and window sizes

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Abstract

An adequate window system is one of the most important retrofit strategies for effective energy conservation of a building, because the U-value and solar heat gain coefficient of windows have enormous impact on the heating and cooling loads of buildings. Therefore, this paper presents methods for improving the energy efficiency of existing residences that have various window sizes and envelope insulations, through a window retrofit using optimal U-value and solar heat gain coefficient values. Furthermore, the window retrofit strategy has been standardized using analysis of the correlation between the properties of the retrofitted window and energy saving rates. The results show that the annual heating and cooling energy demand decreases by 7.9–16.7% when changing the U-value of the windows in a poorly insulated house, and that the relationship between the lower U-value and energy saving is strong for poorly insulated houses regardless of window size. However, for houses with better insulation and larger window sizes, the total energy usage decreases by 18.4–29.7% when the solar heat gain coefficient is lower, and the energy saving effect of the U-value decreases while that of the solar heat gain coefficient increases.

Practical application: This study was focused on improving the energy efficiency of existing residences by applying retrofitting technology. By exploration of the contribution of the specific qualities of windows and the thermal envelope (insulation) system of buildings via simulation, it was determined that it is necessary to adjust the U-value and SHGC of retrofitted windows, in relation to the thermal performance and window-wall ratio of an existing residence, to achieve high energy efficiency.

Keywords

Building energy efficiency, window retrofit, window-wall ratio, thermal performance of building envelopes

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Introduction

In an effort to reduce energy consumption within the buildings sector, during the last decade, many governments and international organizations have committed significant effort towards improving energy efficiency in existing buildings. For example, the US federal government has provided significant financial assistance to support retrofits of existing buildings, and in 2010, the UK government made a significant commitment to upgrade the energy efficiency of 7 million British homes by 2020, by reducing carbon emissions by 29%. Since 2004, China has undertaken building energy efficiency retrofits for demonstration projects in many cities, exploring technical measures and management methods.[1,2] Furthermore, the South Korean government is now encouraging high energy efficiency in buildings by increasing the number of buildings subject to energy efficiency grade recognition, intensifying the criteria for designing energy-efficient buildings, and adopting an energy consumption certificate system to promote the use of energy-efficient technologies.[3–5]

Figure 1 shows statistical data of the number of residential housing units in South Korea, provided by Statistics Korea. The number of housing units built before 1994 is two million, six hundred thousand, which is 69% of the total number of residential housing units in South Korea. This indicates that the majority of housing units was built over 20 years ago, and that many buildings are likely to have experienced deterioration, and to have low energy efficiency. Therefore, it is necessary for them to be retrofitted using optimal methods to improve their energy efficiency.

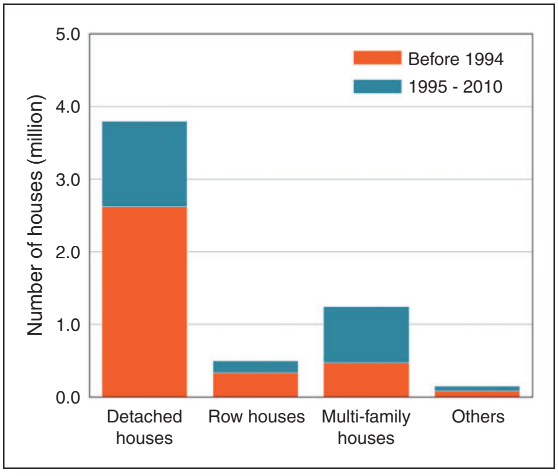

Figure 1. Numbers of residential housing according to year of construction.[6]

Retrofit technologies for reducing energy consumption generally comprise strategies to reduce building heating and cooling loads by replacement of the building envelope and the use of other advanced technologies, e.g. high-performance windows and air-tightness. A significant amount of research has also been performed on developing and investigating different energy efficiency opportunities to improve the energy performance of existing buildings.[7–9] Ardente et al.[10] asserted that the most significant benefits for energy saving are mainly related to improvement in the envelope thermal insulation (high-efficiency windows and thermal insulating boards). Cooperman et al.[11] reported that retrofitting the building envelope is a key step to retrofitting any commercial building for better energy efficiency. Silva et al.[12] showed that an integrated retrofit strategy for single and multi-family buildings, based on a prefabricated retrofit module and on-site renewable energy sources, could present reductions in total energy needs of 83% and 76%, respectively. Liu et al.[2] have shown that the effect of energy efficiency retrofits to existing residences in northern, high heating regions of China can amount to a reduction of 49% in space-heating energy consumption.

Considering only the thermal performance of the building envelopes, however, changes could have a negative affect on cooling loads. Recently, researchers estimated the cooling energy performance of different fenestration systems (various combinations of thermal transmittance, U-value, and solar transmittance, g-value) and different conditions (climate, orientation, and shading) for office and residential buildings.[13–16] They showed that the improved thermal properties of the windows do not contribute to a decrease of the cooling loads; it is the low transmittance (of heat inward) by the advanced window that keeps the cooling loads lower. Buratti et al.[17,18] analyzed the thermal and energetic performance of residential and non-residential buildings by means of two simulation programs and validated the models with experimental data. The results showed that the thermal resistance and solar transmission of glazing have important effects on thermal comfort and reduction of energy demand. Moreover, shading devices for controlling solar heat gains and daylighting through fenestration should be included in sustainable building design by minimizing the amount of direct solar radiation but enhancing the entry of daylight.[19,20]

Heating and cooling loads of a building are connected to the U-value, solar heat gain coefficient (SHGC), and window-wall ratio (WWR). When retrofitting a residential house to increase energy efficiency, the U-value and SHGC of the existing windows should be improved according to the WWR through window replacement. However, although the heating energy is reduced by windows with a lower U-value, because of variation in cooling energy according to the SHGC and WWR within various thermal performance envelopes,[21–24] the optimal combination between the U-value and SHGC is essential. Thus, achievement of high energy efficiency is not just about application of high--performance materials. Therefore, in this study, we evaluate the heating and cooling energy demand of reference residential housing using an energy simulation program. Existing windows were retrofitted, and we then analyzed the correlation between window performance properties, under various WWR and the thermal performance combinations of residential building envelopes.

Methodology

Reference residential house

The floor plan of the reference residential house (Figure 2, provided by the Korea Rural Community Corporation in conjunction with the Ministry of Agriculture, Food, and Rural Affairs of South Korea government) was designed to reduce the cost of designing a home by standardizing floor plans and building materials, with the aim of modularization in rural areas.[25] The floor plans include 26 different types with floor area ranging from 40 m^2 to 125 m^2 according to the number of family members and the living environment. We selected a two-person family house plan with a floor area of 66.64 m^2 (Figure 2(a)).

Because the tendency of heating and cooling energy consumption is affected by thermal

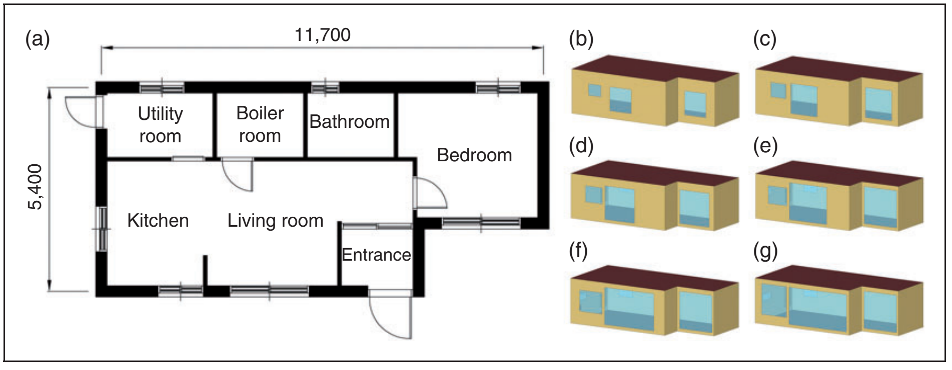

Figure 2. (a) Floor plan of the reference residential house, illustrations of building model according to WWRs; (b) 20%, (c) 30%, (d) 40%, (e) 50%, (f) 60%, and (g) 70%.

performance of the building envelope and WWR,[26–28] it is necessary to consider the various insulation grades of existing housing envelopes and WWRs when retrofitting windows. Thus, the insulation grade of the reference residential housing unit was classified in four levels, the U-values of construction for each level were determined based on the Korea Building Code from the 1970s (level 1: bad insulation) to the 2000s (level 4: good insulation) as listed in Table 1. The building envelopes consisted of reinforced concrete (150 mm), an XPS insulation board ranging from 20 mm to 70 mm considering the different insulation levels, and a gypsum board (10 mm). Figure 2(b) illustrates the building model with various WWRs (20–70% in discrete steps of 10%) from the south. Consequently, we set 24 types of reference house as the baseline: four levels of thermal properties and six WWRs.

Modeling the buildings

To evaluate the thermal performance of a retrofit window according to the WWR and insulation grades of a reference residential house, we calculated the annual heating and cooling energy demands using EnergyPlus. Building modeling was performed in the program SketchUp with parameters determined using the Open-Studio v8.0 plug-in provided by EnergyPlus. The building was assumed to be located in Seoul, South Korea (36 N, 127 E) with a southerly aspect, corresponding to a mixed-humid climate zone.[29] The 30-year average outdoor temperature and global solar radiation are listed in Table 2.[30] The internal loads and the infiltration rate are listed in Table 3, and the schedules of occupancy and lighting, with thermostat set-points for heat and cooling, are shown in Figure 3. Generally, air permeability can be reduced by refurbishing the building

Table 1. U-value of envelopes of the reference housing unit.

Constructions	Level 1 (bad insulation)	Level 2	Level 3	Level 4 (good insulation)
Exterior wall	1.05	0.82	0.58	0.46
Roof	1.05	0.80	0.56	0.28
Basement	1.71	1.14	0.57	0.51
Exterior window	3.49	3.40	3.37	3.40

Units: W/(m^{2}K).

Table 2. Outdoor temperature and global solar radiation of Seoul, Republic of Korea.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Outdoor temperature (°C)	−2.4	0.4	5.7	12.5	17.8	22.2	24.9	25.7	21.2	14.8	7.2	0.4
Solar radiation (MJ/m^2)	219	276	389	471	521	477	369	391	366	329	214	187

Table 3. Input parameters for simulation.[36]

Internal heat gains Equipment	Lighting	Occupancy	Infiltration rate (ACH)
10 W/ m^2	15 W/ m^2	120 W/ person	0.9 h^{-1}

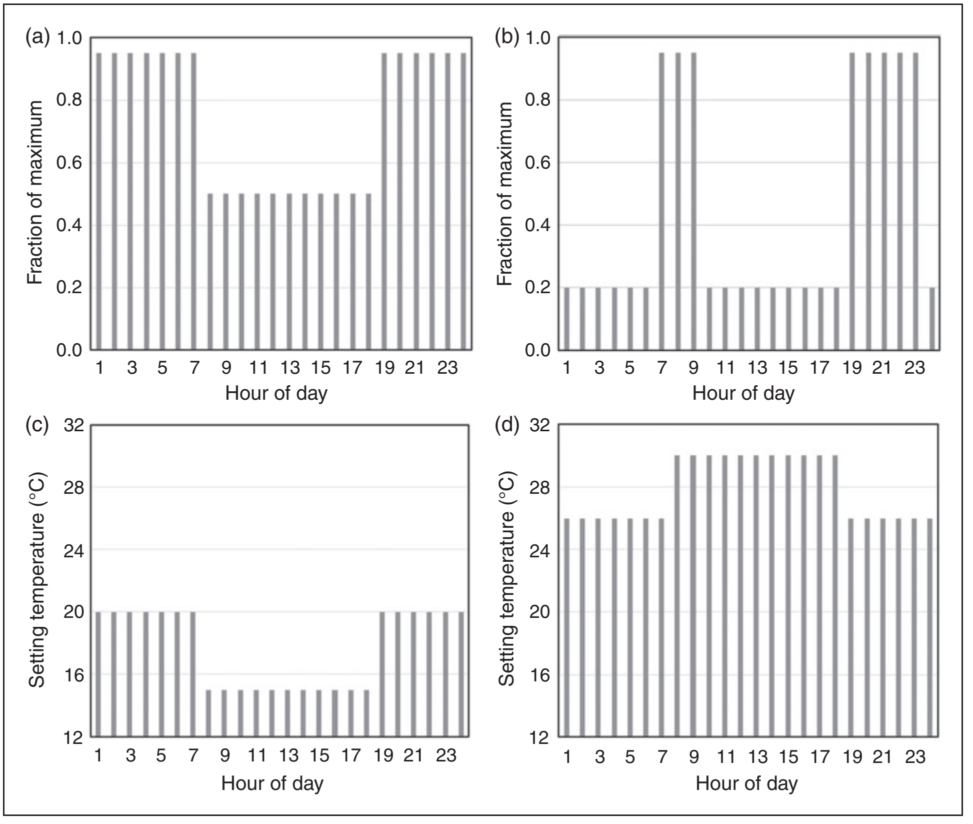

Figure 3. Occupancy and lighting schedules, and temperature settings for heating and cooling: (a) occupancy, (b) lighting, (c) heating, and (d) cooling.

envelope, and this affects the heating and cooling energy demands in buildings.[31] However, quantitative analysis has not been performed deeply when the only window is changed in South Korea. Therefore, in this study, we assumed that the simulation of the reference house is operated under the fixed infiltration rate.

In order to determine how to apply the window retrofitting, the U-value of the windows had five levels: 1.0, 1.4, 2.1, 2.8, and 3.4 W/(m^{2}K), according to Korean window-rating regulations,[32] and the SHGC was classified into five levels: 0.14, 0.28, 0.42, 0.56, and 0.70. First, in the simulation study, each five level of U-values and SHGCs of the new windows are applied to the six type of WWR cases. Second, these 150 cases were applied in relation to four insulation levels of the baseline house. Therefore, we conducted 600 energy simulation cases, as follows

$$\textbf{retrofit cases} = f(L_n, W_k, U_x, S_y) \tag{1}$$

where L_n represents the insulation level of the reference house envelopes, $n = 1, 2, 3, 4$.

W_k represents the WWR on the southern facade, $k = 20\%, 30\%, 40\%, 50\%, 60\%, 70\%$.
U_x represents the U-value of the retrofitted window, $x = 1.0, 1.4, 2.1, 2.8, 3.4$ [W/(m^{2}K)]
S_y represents the SHGC of the retrofitted window, $y = 0.14, 0.28, 0.42, 0.56, 0.70$.

The 'Ideal Loads Air System' of EnergyPlus was used, in order to focus on the performance of the window rather than the details of specific heating, ventilation, and air conditioning systems.[33] In addition, 'Group Simulation Command' mode in EnergyPlus was operated to conduct the various simulation cases simultaneously.

Simulation results of the reference residential housing

The effects of the window retrofits on the heating and cooling energy demand of the reference house, according to the various insulation levels and window sizes were investigated. The findings are discussed in the following subsections.

Simulated results for baseline reference house

For the baseline, the energy demands for heating and cooling the model reference houses, considering both insulation levels and WWRs, are shown in Table 4 and Figure 4. For the cases from level 1 to level 4 (i.e. bad to good envelope insulation), the heating energy required tended to decrease by 29.2–45.5% and the cooling energy increased by 115.7–204.8%, according

Table 4. Heating and cooling energy demand according to insulation levels and WWRs in the reference residential housing unit.

Window-wall ratio (WWR) (%)	Level 1			Level 2			Level 3			Level 4		
	Heating	Cooling	Total	Heating	Cooling	Total	Heating	Cooling	Total	Heating	Cooling	Total
20	109.1	19.7	**128.8**	94.2	26.9	**121.1**	75.5	39.7	**115.2**	59.5	42.5	**102.0**
30	110.6	21.3	**131.9**	97.0	30.2	**127.2**	79.3	46.1	**125.4**	64.1	50.7	**114.8**
40	112.3	22.8	**135.1**	99.5	33.3	**132.8**	82.6	52.1	**134.7**	68.1	58.3	**126.4**
50	115.2	25.7	**140.9**	103.3	39.4	**142.7**	87.6	63.8	**151.4**	74.1	72.6	**146.7**
60	118.4	29.0	**147.4**	107.4	47.0	**154.4**	92.8	76.6	**169.4**	80.2	87.1	**167.3**
70	121.7	33.4	**155.1**	111.5	56.0	**167.5**	98.0	90.0	**188.0**	86.2	101.8	**188.0**

Units: kWh/(m^{2}a).

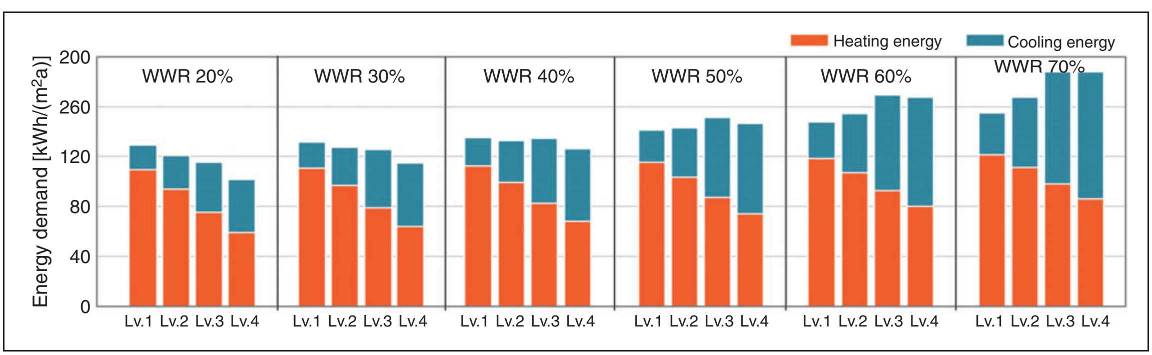

Figure 4. Heating and cooling energy demands according to insulation levels and WWRs in the reference residential housing unit.
WWR: window-wall ratio.

to the WWR. In the 20% to 40% WWR cases, the envelope thermal performance increased from level 1 to level 4, and the total energy demand decreased by 6.4–20.8%, because the heating energy decreased by 36.4–45.5%, even though the cooling energy increased 1.2–1.6 times. This indicates that heat loss through the external envelope of the building has more effect on the total energy demand than the heat gain from solar radiation, in the low WWR case. However, in the 50% WWR case, the envelope thermal performance increased, and the total energy demand increased by 4.1%, because the cooling energy increased by about 1.8 times, despite the decrease in heating energy of 35.7%. In addition, this tendency can also be seen clearly in the cases of high WWR, such as 60% and 70%. This is because the solar heat gain in the indoor space, received through the large window during the day, is prevented from being conducted to the outside by the high thermal resistance of the opaque facades.

Effect of U-value of retrofitted window

Generally, the heating and cooling energy of a building can be reduced by retrofitting with better building fabric. Improvements in the U-value of the envelope, such as the exterior walls and windows, are the most common way of enhancing energy efficiency. Because the whole simulation presents an extensive result, several representative simulation results are shown in Figure 5. The simulation describes a comparison of the heating and cooling energy for each type of baseline, when changing the U-value of the window from 3.4 to 1.0 W/(m^{2}K) at 0.7 of SHGC. For the level 1 case, which had a higher heating energy rate, the U-value was lower and the heating energy decreased by 9.8–27.8%, according to the WWR. Thus, the total energy decreased by 7.9–16.7% and a higher energy saving rate appeared for the case with large WWR. The level 2 case showed a trend similar to that at level 1. When the WWR was higher, it could be seen that the high thermal resistance of retrofitted windows becomes a factor that increases the demand for cooling energy, rather than reducing it.

The greater the level of insulation (e.g. levels 3 and 4), the more the high thermal resistance of the window increased the cooling energy demand. At level 4, in particular, there was little change in the energy demand, and there was similar energy demand for heating and cooling. This was because the cooling energy increased by 9.6–38.4%, according to the WWR, despite the decrease in heating energy of 21.3–45.0%, when the U-value was lower. Therefore, it was clear that when window retrofitting, the U-value had greater influence on the enhancement of energy efficiency in houses with low thermal performance.

Effect of SHGC of retrofitted window

A high SHGC value means that the building gains considerable solar heat through its window system, which has a positive effect during the winter season via heating energy reduction, but a negative effect during summer in terms of cooling energy reduction (i.e. energy demand for cooling increases). However, when retrofitting a house that has a high cooling energy demand, such as levels 3 and 4 with large WWRs, it is necessary to change the SHGC to a lower value. Figure 6 shows a comparison of heating and cooling energy in each type of baseline, when changing the SHGC value of the window from 0.70 to 0.14. At level 1, which is the lower cooling energy rate, the SHGC value is lower and the cooling energy decreased by 13.7–53.0%, according to the WWR, whereas the heating energy increased by 9.8–17.1%. However, despite the significant reduction in cooling energy, the total energy increased by 2.0–6.2%, because the heating energy rate is much higher than the cooling energy at level 1 (i.e. a house with bad insulation).

At level 2, even the cases with small windows (from 20% to 40% WWR) also showed similar trends as at level 1, when the WWR was higher and the SHGC was lower, there was decreasing

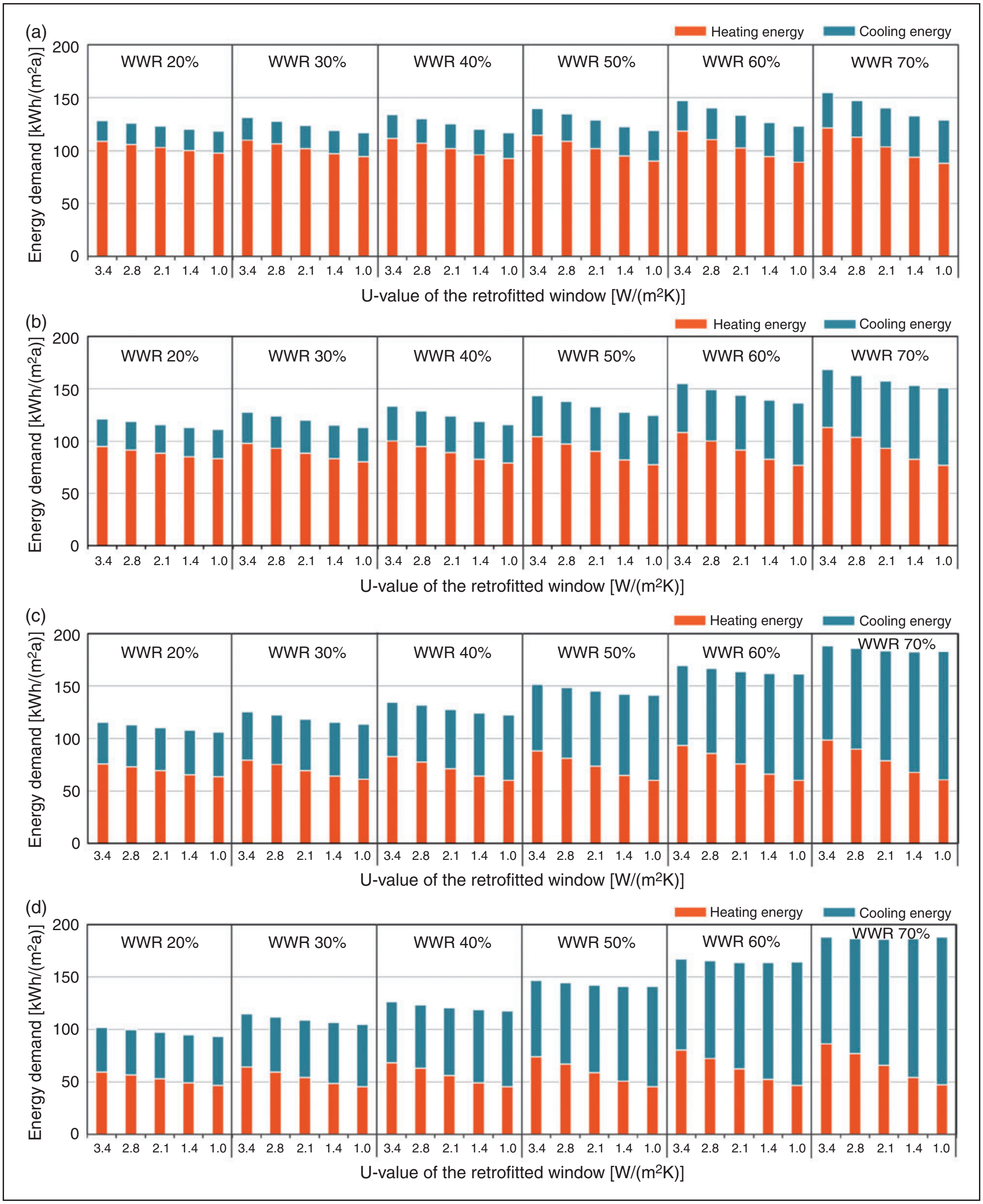

Figure 5. Annual heating and cooling energy according to U-value and WWR at (a) level 1, (b) level 2, (c) level 3, and (d) level 4.
WWR: window-wall ratio.

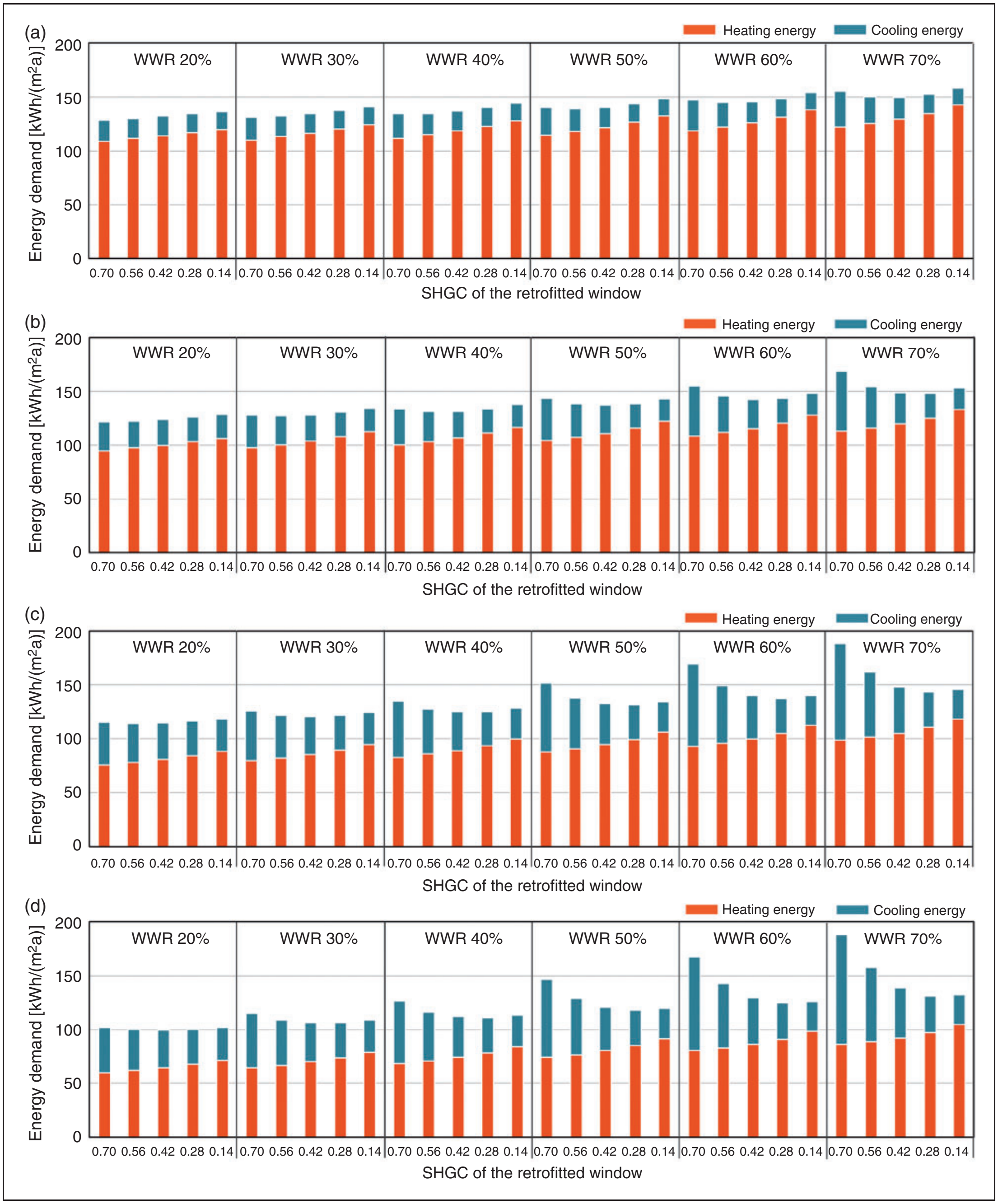

Figure 6. Annual heating and cooling energy according to SHGC and WWR at (a) level 1, (b) level 2, (c) level 3, and (d) level 4.
WWR: window-wall ratio; SHGC: solar heat gain coefficient.

trend in a total energy demand because the saving rate of cooling energy was more than the increasing rate of heating energy. The number of cases of reduction in total energy demand increased when the insulation level was higher (e.g. levels 3 and 4) because solar radiation could not be transmitted through a window with a low SHGC value. Especially at level 4, which had similar heating and cooling energy demand, the SHGC was lower and the cooling energy decreased by 27.3–73.2% due to reduction of the indoor heat gain, whereas the heating energy increased by 19.5–23.3%. Furthermore, when the WWR was higher, the rate of decrease of cooling energy was greater than the rate of increase of heating energy. Thus, the total energy demand was reduced by up to 29.7% in cases with large WWRs. Therefore, the SHGC of the window offers the advantage of energy efficiency when the house is well insulated and retrofitted with large windows.

Discussion

Energy saving rates of retrofitted windows

The results of the entire simulation of the window retrofit in the previous paragraph are arranged in order of energy savings rate in Figure 7. In this chart, the U-value is red, SHGC blue, and the darker colors indicate lower values.

At level 1, which is a house with bad insulation, a lower U-value tended to increase the energy saving rate in the case of 20% WWR, and this trend was stronger when the window size is larger. Although a higher SHGC tended to increase the energy saving rate to a certain degree for cases with smaller windows, it showed an irregular pattern in all cases. At level 2, a lower U-value also tended to increase the energy saving rate in all cases; with the highest energy saving rate shown with 50% WWR. Even though a lower SHGC tended to increase the energy saving rate to a certain degree for cases with larger windows, it showed an irregular pattern in all cases.

At level 3, when WWR was 20%, a lower U-value resulted in a higher savings rate, whereas the SHGC shows an irregular pattern. On the other hand, for the case of 70% WWR, a lower SHGC tended to increase the energy savings rate, whereas the U-value showed an irregular trend. This indicates that the U-value of the window has a strong influence on energy saving when a house with smaller windows is retrofitted. Furthermore, when the window size was larger, the effect of the U-value decreased and that of the SHGC increased in level 3 houses. In addition, this tendency was extreme in houses with high thermal performance, such as the level 4 case. In cases with smaller windows, a lower U-value tended to increase the energy savings rate, whereas the SHGC showed an irregular pattern. On the other hand, for cases with larger windows, a lower SHGC resulted in a higher savings rate, whereas the U-value showed an irregular trend.

Therefore, the U-value of the window had a strong influence on energy saving when retrofitting a house with bad insulation whatever the window size, whereas the SHGC did not affect the energy saving when retrofitting a house with bad insulation. In addition, when a well-insulated house with small WWR was retrofitted, the energy performance was affected by the heating load (thermal resistance performance of the building envelope). A house with a large WWR was affected by the cooling load due to the indoor heat gain from solar heat received through the windows, as well as from the heating load.

Analysis of correlation between U-value and SHGC of retrofitted windows

Pearson's correlation coefficient is a measure of the linear relationship between two variables.[34,35] The covariance is defined by the sum of the cross products of the centered variables, unadjusted for the scale of the variables. Historically, it is the first formal measure of correlation and it is still one of the most widely used measures of relationship. The Pearson's

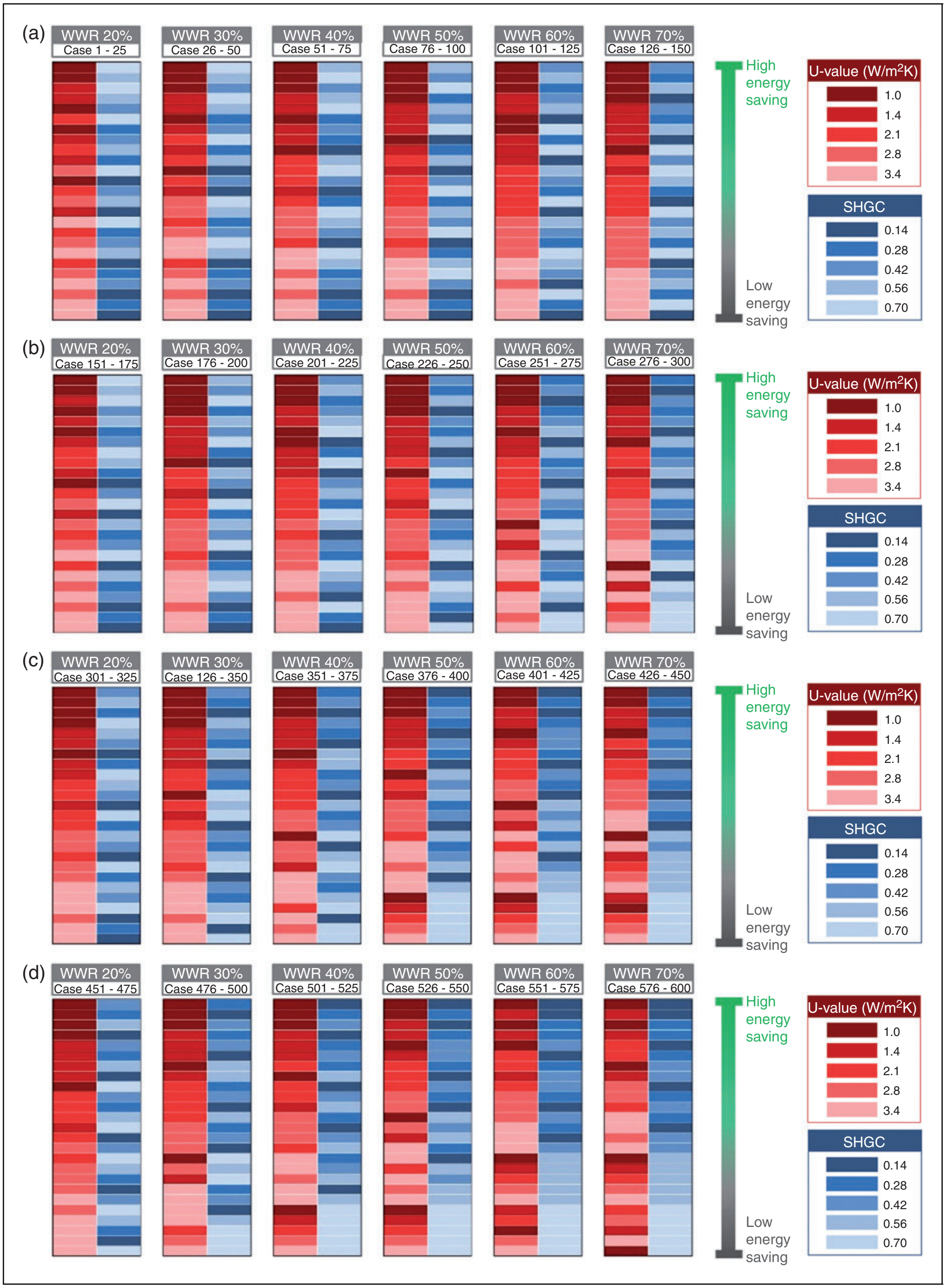

Figure 7. Simulation results arranged in order of energy saving rate at (a) level 1, (b) level 2, (c) level 3, and (d) level 4.

correlation coefficient of the two variables X and Y is formally defined as the covariance of the two variables divided by their standard deviations (as a normalization factor), and it can be defined equivalently by

$$r_{XY} = \sum_{i=1}^{n} \frac{X_i - \overline{X}}{\sqrt{\sum_{k=1}^{n} \left(X_k - \overline{X}\right)^2}} \frac{Y_i - \overline{Y}}{\sqrt{\sum_{k=1}^{n} \left(Y_k - \overline{Y}\right)^2}} \quad (2)$$

A correlation, indicated by r_{XY} that is close to '1', indicates a positive relationship between X and Y, and if close to '0', indicates the absence of a relationship between the two variables. Furthermore, a correlation of between 0 and 0.3 indicates a weak linear relationship, between 0.3 and 0.7 indicates a moderate linear relationship, and between 0.7 and 1.0 indicates a strong linear relationship.

Figure 8 shows the correlation between the U-value and SHGC of retrofitted windows for energy efficiency by Pearson's correlation coefficient analysis. At level 1, the relationship between the U-value and energy saving rate appeared strong (>0.7) for all window sizes, whereas the relationship between SHGC and energy saving rate appeared moderate when the WWR ranged from 20 to 40%, and weak when WWR was 50–70%. At level 2, the U-value also had a strong relationship with the energy saving rate for all WWR cases, even though it showed a decreasing trend for larger window sizes. On the other hand, the relationship between SHGC and energy saving rate strengthens from weak to moderate for increasing window sizes. At level 3, the energy saving effect of the U-value showed a strong relationship in cases with smaller windows, such as WWR of 20% to 40%; however, when the WWR was higher, the relationship with U-value became moderate. Conversely, the relationship of SHGC displayed an increasing trend when the WWR was higher, and showed a strong relationship for the cases of 60% and 70% WWR. In addition, this tendency appears stronger at level 4. The effect of the U-value decreased more sharply than at level 3 and showed a strong relationship only for WWR of 20% and 30%. However, the effect of SHGC increased in a larger range when the size of the retrofitted window was larger. The relationship between SHGC and energy saving rate strengthened from weak to moderate for increasing window sizes from 20% to 40%, and appeared strong when WWR was 50% to 70%.

Conclusions

Although it is advantageous in terms of heating load to use windows with lower U-value, an optimal combination between the U-value and SHGC should be considered for high energy efficiency, because the cooling energy usage varies according to the combination of SHGC and WWR. Thus, we proposed a window retrofit strategy to reduce the heating and cooling energy variation of a residential house, depending on the insulation level and WWR.

The following summarizes the main findings of this study:

(1) Simulation of the heating and cooling energy demands of baseline houses with various insulation levels and WWRs was conducted using the EnergyPlus energy simulation program. For cases with small WWR, the total energy demand decreased when the insulation performance of the envelope was higher. However, when WWR was 50% to 70%, the thermal performance of the envelopes was higher and the total energy demand increased. This was because the cooling energy increased significantly because the solar heat gain in the indoor space, received through the large window during the day, was prevented from being conducted to the outside by the high thermal resistance of the opaque facades.

(2) Generally, enhancing energy efficiency by the retrofit method occurs by improvement of the thermal performance of the building envelope. In a house with low thermal performance, the U-value of retrofitted windows

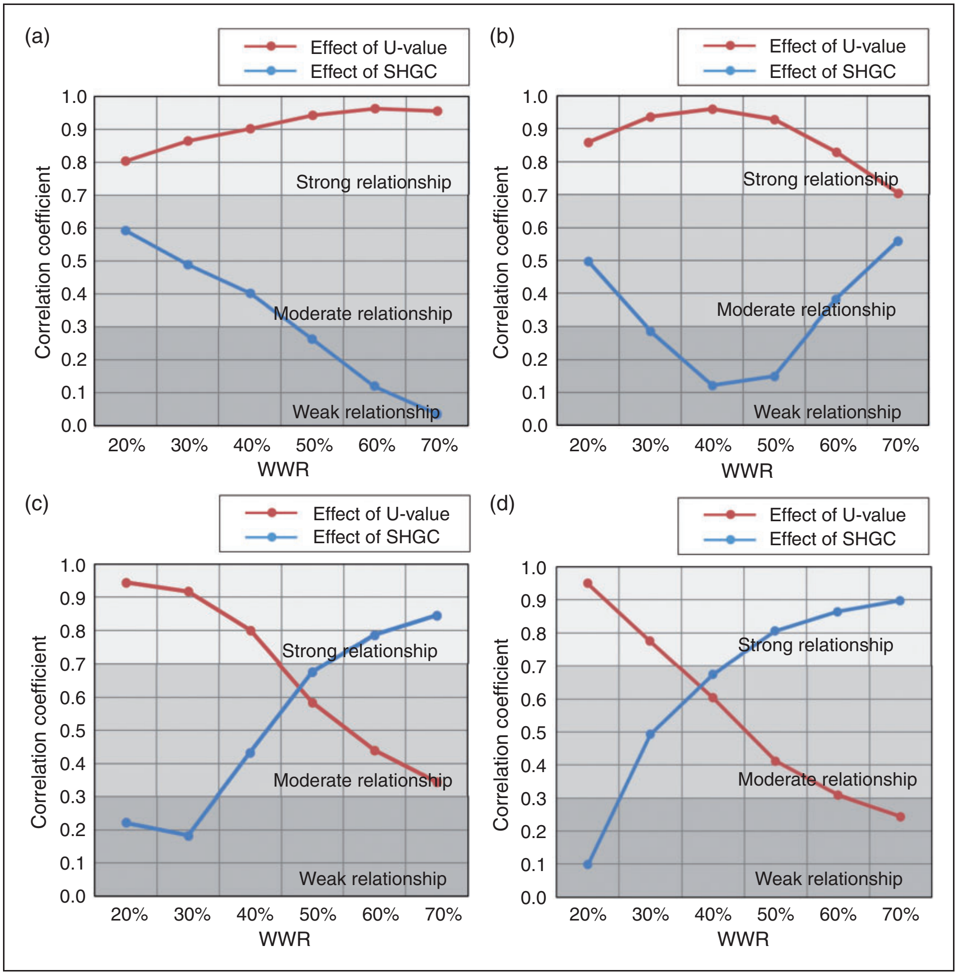

Figure 8. Correlation analysis between properties of retrofitted windows and energy saving rate at (a) level 1, (b) level 2, (c) level 3, and (d) level 4.

was lower and the total energy demand decreased regardless of the WWR. However, the greater the level of insulation, the more the high thermal resistance of the window influenced the increase in the cooling energy demand. Thus, in the well-insulated house, the total energy decreased slightly, or remained constant, when the U-value of the window was lower, because the decrease in the rate of heating energy was similar to the increase in the rate of cooling energy. Conversely, when the SHGC of the window in the well-insulated house with large windows was lower, the total energy demand decreased considerably due to reduction of indoor heat gain from the solar heat, whereas the SHGC did not related to change in total energy demand in the badly insulated house.

(3) In the correlation analysis between properties of retrofitted windows and energy saving rate, the U-value of the window was shown to have a strong influence on energy saving when retrofitting a badly insulated house with all sizes of windows, whereas the SHGC did not affect energy saving. The

correlation coefficient between the U-value and energy saving rate was shown to have a strong relationship for all WWR cases, and the relationship between SHGC and energy saving rate remained from weak to moderate for all window sizes. Conversely, for high insulation levels and large windows, the effect of the U-value decreased and that of SHGC increased. Furthermore, the relationship of SHGC displayed an increasing trend when the WWR was higher, whereas the U-value exhibited a decreasing trend.

Conflict of interest

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